ADMINISTRATIVE INFORMATION

1. **Project Name:** Virtual Welded-Joint Design Integrating Advanced Materials And Processing Technologies

2. **Lead Organization:** Caterpillar Inc.
   Technical Service Division
   Peoria, IL 61656-1875

3. **Principal Investigator:** Dr. Zhishang Yang: Phone (309) 578-2761, Fax (309) 578-3157, Email: Yang_Zhishang@cat.com

4. **Project Partners:** Battelle Memorial Institute, Dr. Pingsha Dong
   Colorado School of Mines, Prof. Stephen Liu
   Oak Ridge National Laboratory, Dr. Suresh Babu
   QuesTek Innovations, LLC, Prof. Greg Olson
   The Pennsylvania State University, Prof. Tarasankar DebRoy

5. **Date Project Initiated:** 10/01/2001

6. **Expected Completion Date:** 09/30/2004

PROJECT RATIONALE AND STRATEGY

7. **Project Objective:**

The primary goal of this project is to increase welded - joint fatigue life by 10 times and to reduce energy use by 25 percent through product performance and productivity improvements using an integrated modeling approach. This integrated model will address base material selection, weld consumable design, welding process parameters optimization, weld residual stress management, and fatigue resistance improvement.

8. **Technical Barrier(s) Being Addressed:**

The fatigue strength of welded-joint is currently the bottleneck to design high performance and lightweight welded structures using advanced materials such as high strength steels. Weld bead shape, residual stress, and microstructure are three major factors determining weld fatigue strength. The major technical barriers related to develop fatigue resistant welds for high strength steels include:

- Very limited knowledge and no effective methods available on how to make welds with desired bead shape, residual stress, and microstructure for improved fatigue strength.
- High tensile residual stresses, which accelerate the fatigue crack propagation and reduce weld fatigue life, are usually formed in high strength steel welds.

9. **Project Pathway:**

In order to achieve a high fatigue resistant welded-joint it is necessary to manage the weld bead shape for maximum fatigue strength, produce preferable residual stress distribution, and obtain the desired microstructure for improved material toughness and strength. This is a systems challenge that requires the optimization of welding process, welding consumable, and base material. This project will develop an integrated modeling and simulation tool for addressing these issues in a systems approach.

The integrated approach combines five sub-models: weld thermo-fluid model, weld microstructure model, weld material property model, weld residual stress model, and weld fatigue model. The approach is thus based on interdisciplinary applied sciences including heat transfer, computational fluid dynamics, materials science, engineering mechanics, and material fracture mechanics. The systematic modeling approach will lead to an optimized welded-joint design considering combined effects of weld bead geometry, microstructure, material property, residual stress, and the final fatigue strength. Critical experiments will be carried out in the project to validate the results from simulation.

In particular, a special welding wire will be developed in this project to introduce compressive residual stress at weld toe for the fatigue life improvement in high strength steel welds. Technology for making fatigue resistant welded-joint will be developed in this project for high performance and lightweight fabricated structures.

10. **Critical Technical Metrics:**

Baseline Metrics:

- Current welding phenomena models are isolated and there is no link between welding process parameters and chemical composition, microstructure, residual stress, and the final fatigue performance. It takes months or years to develop a welding consumable and a welding process for an application by using conventional trial and error experimental methods.
- Some important factors to weld fatigue strength such as the weld bead shape in T-fillet welds, the effect of weld microstructure and residual stress on weld fatigue strength cannot be predicted by the existing welding phenomena models.
- High tensile residual stress at the magnitude of the material yield strength normally existed in high strength steel welds. Currently weld fatigue life for high strength steel welds is very limited due to the existing high tensile residual stress. For example, the current fatigue life of F class weld for high strength steel (90 ksi yield strength) is 6×10^4 at the stress level of 300 MPa. The fatigue strength at 1×10^6 cycle is 120 MPa.

Project Metrics:

- An integrated modeling approach will be developed to establish the relations among the welding process-microstructure-property-performance. The integrated model for virtual welded-joint design will reduce the time for new welding material and process development from months/years to hours/days.
- Advanced welding phenomena models such as 3D weld thermo-fluid model and weld fatigue model will be developed in this project to establish the systematic modeling capability.
- A special welding wire will be developed in this project to introduce compressive residual stress in high strength steel welds for fatigue resistance. The compressive residual stress combined with desired weld bead shape will lead to more than 10× fatigue life improvement. For example, the fatigue life of F class weld for high strength steel (90 ksi yield strength) will be increased to more than 6×10^5 at 300 MPa stress level. The fatigue strength at 1×10^6 cycle will be more than 240 MPa.

PROJECT PLANS AND PROGRESS

11. **Past Accomplishments:**

The project partners have made significant progresses in the past two and half years and it is very promising that the project goal can be achieved by the end of this project. The major accomplishments we have achieved so far include:

- A 3D weld thermo-fluid model with free surface has been developed to simulate weld bead formation for Gas-Metal-Arc welding. The model is able to predict weld bead shape for different types of welded-joints including butt welds, T-fillet welds, and plug welds.
- A weld microstructure model, which was originally developed for microstructure calculation in fusion zone, has been extended for weld HAZ by coupling the thermal cycles from thermal model. The modified model is now able to predict the spatial evolution of weld microstructure such as phase transformations and grain growth in both weld fusion zone and its heat affected zone (HAZ).
- The true stress-strain curves at elevated temperatures for both high strength steel and mild steel have been measured using Gleeble machine. A model has been developed to predict the true stress-strain curves based on the experimental data.
- The effect of phase transformation on weld residual stress formation has been incorporated into weld residual stress model.
- A two-stage growth model is being developed to investigate the threshold effects. Crack nucleation and short crack growth are being treated as a continuum in the crack growth regime. The initial results show that the effect of residual stress on weld fatigue life can be quantitatively predicted.
- A special welding wire, which has low martensite transformation temperature, has been developed to generate compressive residual stress for weld fatigue resistance.
- Preliminary fatigue test results indicate that more than 10× fatigue life improvement can be achieved in high strength steel welds by the combination of desired weld bead shape and compressive residual stress.

Future Plans:

- Complete weld fatigue model development (06/30/2004)
- Applying virtual welded-joint design approach for technical demo (07/30/2004)
- Prepare high strength steel weld panels for fatigue test in technical demo (05/30/2004)
- Weld residual stress measurement using neutron diffraction at ORNL (07/30/2004)
- Fatigue test of weld samples for technical demo (09/15/2004)
- Final report (10/30/2004)

12. **Project Changes:**

We plan to take out two subtasks related to laser welding simulation from the project scope due to the tight budget for the ambitious goal proposed in this project.

13. **Commercialization Potential, Plans, and Activities:**

Two major technologies will be generated from this project: (1) an integrated simulation model for virtual welded-joint design and (2) a technology to increase high strength steel weld fatigue strength by the combination of compressive residual stress from special welding wire and the desired weld bead shape from an unique welding process. The integrated model will be able to predict weld bead shape, microstructure, property, residual stress, and final fatigue performance as functions of welding parameters, chemical composition, and workpiece geometry. It can be used in welding community either as a research tool for scientists or as an engineering tool by welding engineers for actual process development and high performance welded-joint design. The significant fatigue strength improvement for high strength steel welds indicates a technology breakthrough. It can have fundamental impact on the application of high strength steels in many industrial sectors such as mining, shipbuilding, bridges, and automotive.

Two major approaches, technical presentations/papers and advisory council meeting, have been taken to market the developed technologies. We have so far made 7 presentations in international conferences and published 4 technical papers to diffuse the developed technologies. We also formed advisory council by inviting representatives from different industrial sectors, researchers from research and national laboratories. An advisory council meeting has been held in Chicago in April 2004. The results we got so far have been presented to Caterpillar business units. Some of them have shown strong interest and have put budget for further evaluation to apply the developed welding wire in their welded structures.

14. **Patents, Publications, Presentations:**

Publications

- Z. Yang, X. L. Chen, N. Chen, H. W. Ludewig and Z. Cao: "Virtual Welded-Joint Design by Coupling Thermal-Metallurgical-Mechanical Modeling", *Proceedings of 6th Intl. Conf. On Trends in Welding Research*, Pine Mountain, GA, April 2002.
- Z. Cao, Z. Yang, and X. L. Chen: "Three-Dimensional Simulation of Transient GMA Weld Pool with Free Surface", *Welding Journal* vol. 83, 2004, p.169s.
- Z. Yang and H. W. Ludewig: "Virtual Welding – Applying Science to Welding Practices", to be published in the proceedings of the 8th Intl. Conf. On Numerical Methods in Industrial Forming Processes.
- Z. Cao, Z. Yang, X. L. Chen and F. W. Brust: "Three-Dimensional Transient Weld Pool Simulation of Gas Metal Arc Welding", in Proceedings of the 2002 International Conference on Computational Engineering and Sciences, ICES 2002, Reno.

Presentations

- Z. Yang, X. L. Chen, N. Chen and Z. Cao: "Virtual Welded-Joint Design – A Systematic Modeling Approach for High Performance Welds", 84th Annual Convention, Detroit, April 2003.
- Z. Yang, X. L. Chen, N. Chen and Z. Cao: "A Systematic Microstructure-Level Modeling Approach For Designing High Performance Welded-Joint", in 2002 Max Intl. AWS Welding Show and 83rd Annual Convention, Chicago, March 2002.
- Z. Cao, F. Brust, X. L. Chen, and Z. Yang: "Numerical Simulation of A 3-D Transient GMA Weld Pool", ibid.
- Z. Yang, X. L. Chen, N. Chen, H. W. Ludewig and Z. Cao: "Virtual Welded-Joint Design by Coupling Thermal-Metallurgical-Mechanical Modeling", in 6th Intl. Conf. On Trends in Welding Research, Pine Mountain, GA, April 2002
- Z. Yang, X. L. Chen, N. Chen, H. W. Ludewig and Z. Cao: "A Systematic Approach for Virtual Welded-Joint Design", PVP 2002.
- Effects of Manganese and Nickel on the Phase Stability of High AlloyWeld Metals. F. Martinez, G. Edwards, and S. Liu. Presented at the AWS Welding Show 2003. April 8th, 2003 Detroit, Michigan High Alloy Weldments for Fatigue Resistance in Structural Carbon Steel.
- F. Martinez, G. Edwards, and S. Liu. Presented at the AWS Welding Show 2002. March 5th, 2002 Chicago, Illinois